Final Report for AOARD 064060

Title: Feasibility of Biodegradable MEMS based on Cellulose Paper

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Goal:

Development of biodegradable MEMS is essential to industry, military and space applications. We have proposed a biodegradable MEMS fabrication with cellulose-based Electro-Active paper (EAPap). Micro-transfer printing (MTP) technique was successfully demonstrated by making interdigit transducer (IDT) pattern for surface acoustic wave (SAW) sensor and micro-strip pattern for rectenna. However there were some technical difficulties including adhesion control and contact pressure control. Thus, we propose to improve the quality of the MTP by studying the adhesive coating, contact pressure and depth control. Also, the feasibility of micro-electronics fabrication on cellulose EAPap will be studied, followed by a simple device demonstration. After that the feasibility of micro-molding with cellulose EAPap will be investigated. These attempts will offer adaptation of MEMS technology with the biodegradable paper and the capability of sensor and actuator functions on it.

Approaches:

We intend to develop Piezoelectric Paper that exhibits merits in terms of flexible, biodegradable, ultra-lightweight and cheap characters by using cellulose. Examples of the types of structures that can be produced are shown in Fig. 1.

Figure 1. Structures that can be made from piezoelectric paper.

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14. ABSTRACT
This report covers investigations of adhesive coatings, contact pressures, and depth control of micro-transfer printing (MTP) on Electro-Active paper (EAPap) and the micro-molding of cellulose EAPap, suitable to production of micro-electronics, such as inertia sensors.

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Electro-active paper(EAPap) has been recognized as a new smart material that can be used for sensors, actuators, bio-mimetic robots, smart wall papers, and so on. EAPap is made with cellulose paper by coating thin electrodes on both sides of it. This paper can produce a bending or longitudinal strain in the presence of electric field. Also, it can produce an induced charge under the external stress. This EAPap material has many advantages in terms of large displacement output, low actuation voltage, low power consumption, dryness, low price, flexibleness, sensing capability and biodegradable characteristics.

Fabrication of biodegradable MEMS with cellulose EAPap is a challenging technology. Because conventional lithography and etching techniques are difficult to be applied, a new idea for micro-fabrication should be provided. It is difficult to apply conventional micro-patterning process and wet process, because this material is flexible and the surface is rough. Furthermore, cellulose paper's hydrophilic nature does not allow wet etching techniques for micro-patterning.

In developing biodegradable MEMS fabrication with cellulose EAPap, there are several sub-technologies; micro-patterning on cellulose paper, fabrication of micro-electronics and micro-structure fabrication with cellulose paper (Fig. 2).

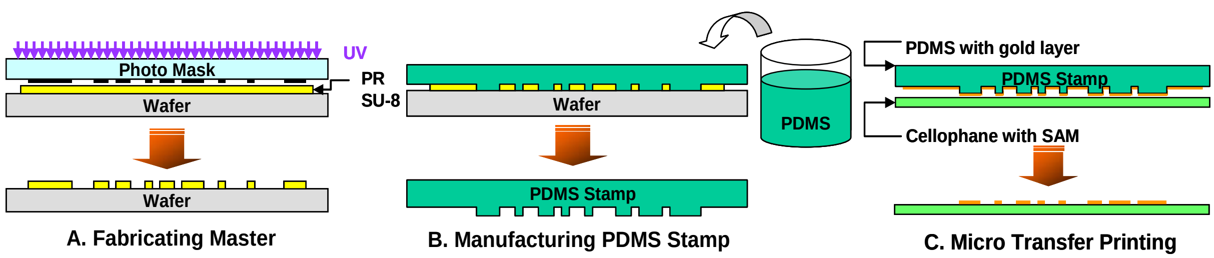

Figure 2. Micro transfer printing (MTP) process.

The plane of work includes the MTP process improvement, the Schottky diode fabrication on cellulose paper and the micro-molding with cellulose paper.

1) Micro-Transfer Printing improvement

The MTP process has been studied to improve the quality of micro-transferred pattern. Studies included adhesion control between gold and cellulose paper, and contact alignment for pattern transfer. Several adhesive layers were tried to improve the adhesion between gold and cellulose papers. Also, the contact aligner machine was revised so as to precisely control the contact pressure and contact depth. This contact control capability allows high yield ratio on the MTP process. To demonstrate its successfulness, dipole rectenna pattern were made.

2) Micro-electronics fabrication

The next topic was the feasibility study of micro-electronics fabrication. As a micro-electronic device, Schottky diodes were fabricated. Instead of using semiconductor materials such as GaAs, GaNb, nano particles were mixed in a resin polymer such as

PEDOT, and their processability on cellulose paper were studied. MTP was used to make a pattern of semiconductor element on cellulose EAPap.

3) Micro-molding with cellulose paper

Lastly, the feasibility of micro-molding with cellulose paper will be investigated. So far, the cellulose paper fabrication was successfully established. We are able to make any kind of cellulose solution. To make micro-structures with cellulose paper, micro-molding can be a solution. Cellulose solution can be poured onto a micro-mold, and cured. After that, however washing and drying process should be followed, which may affect the quality of the micro-molding. This effect will be investigated and how to improve its quality will be studied.

4) Characterization

The piezoelectric measurement system is shown in Fig. 3. The applied voltage was 1-9 V, the applied frequency was 0.2-0.5 Hz, the temperature was 20^{o}C, and the relative humidity was 20-22%.

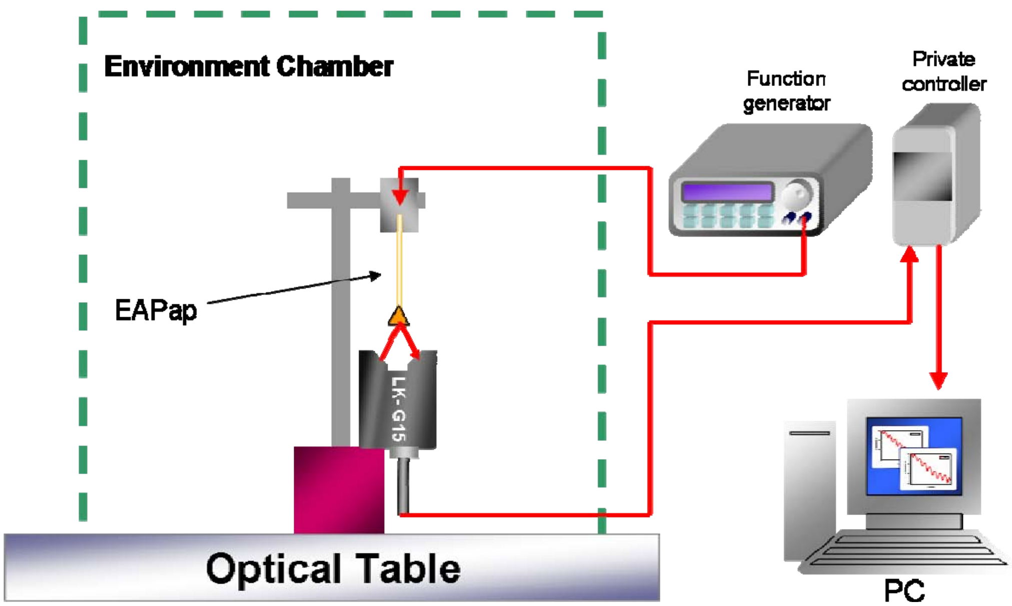

Figure 3. Measurement of converse piezoelectricity.

Results:

The first main result is that piezoelectric paper was fabricated successfully. Cross-sectional views are shown in Fig. 4. The paper contained cellulose nanofibers, which was composed of cellulose crystalline and cellulose chains. The cellulose chains could be ordered by electrical poling and stretching. The diameters of the cellulose nanofibers were gradually reduced by increasing the stretching ratio. Dense crystalline in nanofibers of diameter 50-100 nm and ordering of cellulose chains resulted (Fig. 5).

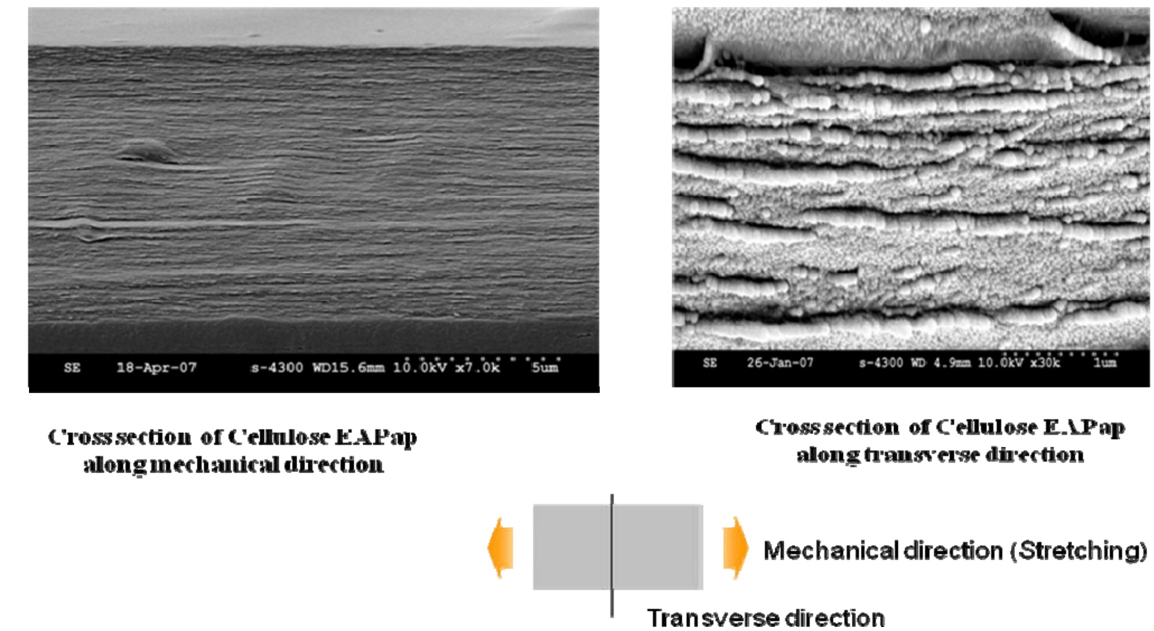

Figure 4. View of piezoelectric paper.

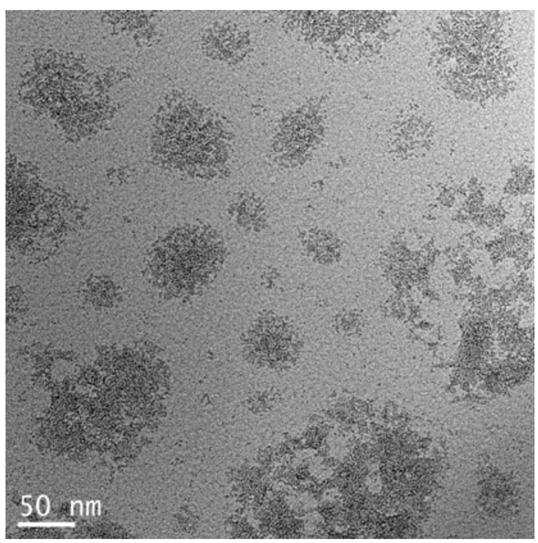

Figure 5. Crystalline nanofibers revealed by high-resolution transmission electron microscopy.

Preliminary measurements revealed existence of direct piezoelectricity (Fig. 6) and converse piezoelectricity (Fig. 7).

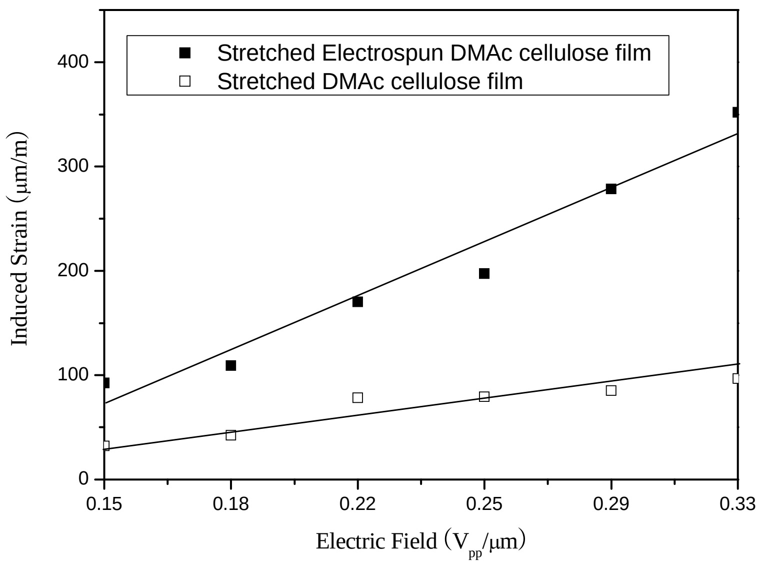

Figure 6. Direct piezoelectricity in paper sample.

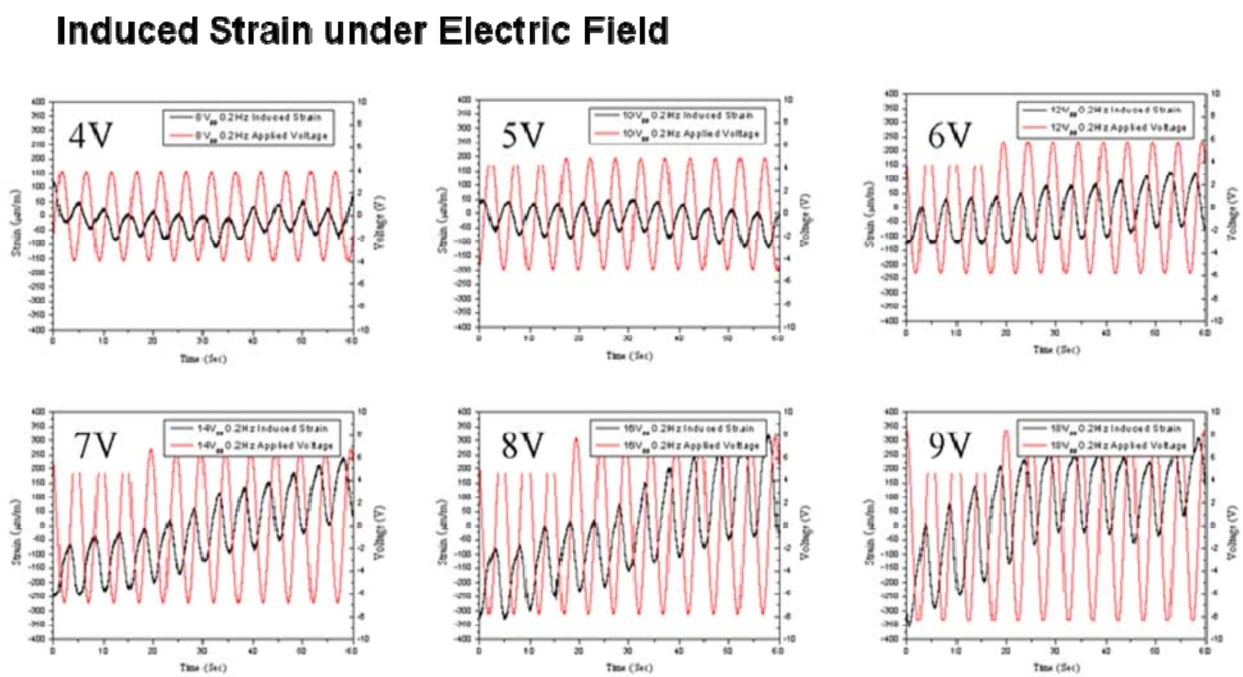

Figure 7. Converse piezoelectricity in paper sample.

Future Plans:

Our future plans consist of the following tasks:

1. Improvement of Piezoelectric Paper made with Cellulose
   - Ion elimination during the paper fabrication process
   - Mechanical stretching of cellulose paper for aligning cellulose
   - High magnetic field for aligning cellulose
   - Piezoelectric effect characterization
2. Paper Speaker made with Piezoelectric Paper
   - Demonstration of piezoelectric paper
   - Frequency band: 500-20,000 Hz
   - Feasibility test of ultrasonic transducer with piezoelectric paper
3. Structural Health Monitoring Patch
   - Another application demonstration of piezoelectric paper
   - Based on Surface Acoustic Wave (SAW) for power less sensor patch
   - IDT fabrication on cellulose piezoelectric paper